

PRIMORDIAL BINARIES AND INTERMEDIATE MASS BLACK HOLES IN GLOBULAR CLUSTERS

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Draft version February 5, 2008

ABSTRACT

We present the first study of the dynamical evolution of a star cluster that combines a significant population of primordial binaries with the presence of a central black hole. We use direct N-body simulations, with a black hole mass of about one percent of the total mass of the cluster.

The evolution of the binary population is strongly influenced by the presence of the black hole, which gives the cluster a large core with a central density cusp. Starting from a Plummer profile, we first encounter a phase, that last approximately 10 half-mass relaxation times, in which binaries are disrupted faster compared to analogous simulations without a black hole. Subsequently, however, binary disruption slows down significantly, due to the large core size.

The dynamical interplay between the primordial binaries and the black hole thus introduces new features with respect to the scenarios investigated so far, where the influence of the black hole and of the binaries have been considered separately. Specifically, the pattern of binary destruction by an intermediate-mass black hole may leave a fingerprint that could be detected observationally.

Subject headings: stellar dynamics — globular clusters: general — methods: n-body simulations — binaries: general

1. INTRODUCTION

Over the last few years some tantalizing, but yet far from conclusive, evidence has been accumulating in support of the idea that some star clusters could harbor a central black hole (BH) with a mass of the order of $10^3 M_\odot$ or more. Detection of such an intermediate mass black hole (IMBH) has been claimed for *M15* and *G1* (Gerssen et al. 2003; Gebhardt et al. 2002, 2005), although accurate dynamical models of *M15* and *G1* can be obtained without a central BH (Baumgardt et al. 2003a,b). Interestingly, the visual appearance of globulars containing an IMBH is not that of a so-called core-collapsed cluster, but rather that of a cluster with a still sizable core (Baumgardt et al. 2005).

IMBHs present a high theoretical and observational interest as these could be potential ultra-luminous X-ray sources and even emit gravitational waves, detectable by the next generation of gravitational wave detectors, as a result of close interactions with stars. However, despite this interest and the fact that theoretical studies of BHs in stellar systems started more than 30 years ago (e.g., see Peebles 1972; Bahcall & Wolf 1976), detailed direct N-body simulations to study the dynamics of an idealized model with single stars and a central BH have been performed only recently (Baumgardt et al. 2004a,b; see also the studies on the formation of IMBHs by runaway mergers of massive stars by Portegies Zwart et al. 2004).

One ingredient that complicates N-body simulations of globular clusters is the presence of primordial binaries. Often, these are neglected in large simulations despite the increasing observational evidence that many stars in a globular cluster have a companion (Hut et al. 1992; Albrow et al. 2001; Bellazzini et al. 2002; Zhao & Bailyn 2005). This frequent neglect

is due to the dramatic increase in computational resources required in a simulation where the local dynamical timescale may be many orders of magnitude smaller than the global relaxation timescale (hard binaries have an orbital period of a few hours, while the half-mass relaxation time can be up to a few billion years). The study of the dynamics in the presence of primordial binaries has been mainly limited to Fokker-Planck or Monte Carlo approaches (Giersz & Spurzem 2000; Fregeau et al. 2003) and to direct simulations with rather modest particle numbers, from $N \approx 10^3$ (McMillan et al. 1990; McMillan & Hut 1994; Heggie & Aarseth 1992) to recent higher resolution simulations, with N up to 16384 (Heggie et al. 2005). Some realistic simulations, including primordial binaries are available (Portegies Zwart & McMillan 2004), but these are limited only to the first stage of the life of young dense clusters. In the case of open clusters, *M67* has been modeled in a 36,000-body simulation running for several Gigayears (Hurley et al. 2005).

The presence of either an IMBH or a significant population of primordial binaries leads to an early release of abundant energy, inhibiting the development of a deep core collapse and hence of the onset of gravothermal oscillations. An IMBH can generate energy by swallowing or tightly binding stars deep in its potential well [note also that energy can be generated through encounters of stars in the density cusp that is formed around the BH], while primordial binaries can generate energy by rapidly increasing binary binding energy through three and four body encounters. Energy thus generated in the core of the system fuels the expansion of the half-mass radius, leading to a self-similar expansion of the entire system (Hénon 1965).

In this work we present the first direct simulations of the evolution of globular clusters with both a significant fraction of primordial binaries (10 %) as well as an IMBH with a mass of 1.4 – 2.5 % of the total mass of the system. We address the following questions. Under the

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combined effect of the BH and of the binaries, what is the equilibrium size of the cluster core? How is the binary population affected by the presence of the central IMBH? Which physical processes dominate in the core? In principle two competing effects are possible: the BH may either enhance the disruption rate of binaries both indirectly, due to the creation of a density cusp, and directly, by tidal stripping (Pfahl 2005), or it may reduce the probability of interactions between binaries and singles, by producing a low stellar density in a relatively large core (Baumgardt et al. 2004a). Which process is dominant is of fundamental importance. These questions are addressed in the next sections.

2. NUMERICAL SIMULATIONS: SETUP

The simulations presented in this paper have been performed using the NBODY-6 code (Aarseth 2003), that has been modified with the kind help of Dr. Aarseth to ensure a more efficient and accurate treatment of the dynamics around the BH (the relative energy error at the end of our simulations is below 0.5 %). We used a total of $N_{tot} = 9011$ equal mass stars (each of mass m), arranged in 819 binaries and 7373 singles, plus a BH, introduced as a massive star, with mass (m_{BH}) in the range 1.4 – 2.5 % of the total mass of the system. The system is isolated and the initial binding energy distribution for the binaries is in the range 3 to 400 kT (where $3/2 kT$ is the average kinetic energy of a star of the system), flat in logarithmic scale as in the runs by Heggie et al. (2005), that we use for comparison, as here we employ the same initial conditions except for the presence of the BH. The initial mass distribution is that of a Plummer model. To initialize the simulation in a situation of approximate dynamical equilibrium in the presence of the BH we generate a Plummer model made of single stars only, we then scale the velocities of the particles to reach virial equilibrium and let the system evolve for 5 half-mass crossing times. Some stars are then selected at random and binaries are added to the simulations, with the standard initialization provided by NBODY-6. The evolution of the system is then followed up to $t \approx 25 t_{rh}(0)$. For $t_{rh}(0)$ we mean t_{rh} computed at $t = 0$. Here t_{rh} is the half-mass relaxation time (Spitzer 1987), defined as $t_{rh} = 0.138 N r_h^{3/2} / (\sqrt{MG} \ln(0.11N))$, with r_h being the half-mass radius, M the total mass of the system and N the number of centers of mass (i.e. $N = 8192$ in our case); in NBODY units $t_{rh}(0) \approx 112$ for our initial conditions.

3. GLOBAL EVOLUTION

The large scale structure evolution of the cluster is dominated by the heating related to the presence of the BH. In fact only the inner regions of the system experience a mild collapse on a timescale that, depending on the mass of the BH, is of the order of a few t_{rh} . Inside the core radius r_c , defined as the density averaged radius (Casertano & Hut 1985), a cusp in the density profile is formed within the sphere of influence r_i (with $r_i \approx 15 r_c m_{BH}/M$, see Baumgardt et al. 2004a) of the BH, with a profile proportional to $\approx 1/r^{1.7}$ and thus similar to the $1/r^{1.75}$ measured by Baumgardt et al. (2004a). For $m_{BH} = 0.014M$ the influence radius is approximately $0.2r_c$. By definition, the stellar mass within

TABLE 1
SUMMARY OF RUNS WITH $N = 8192$

m_{bh}/M	f	$(r_c)_{cc}/r_{c0}$	r_c/r_h	r_{hf}/r_{h0}
0.014	0.1	0.75	0.29	2.46
0.025	0.1	0.80	0.31	2.83
0.014	0	0.70	0.27	1.92
0	0.1	0.25	0.09	2.25

NOTE. — In the first column we report the BH mass, in the second the fraction f of primordial binaries, in the third the core radius at the end of the initial core contraction phase $(r_c)_{cc}$ in units of the initial core radius r_{c0} , the fourth entry is the core to half mass radius ratio during the self-similar expansion of the system, while the last entry (r_{hf}) is the value of the half mass radius at $t = 24 t_{rh}(0)$ in units of the initial half mass radius.

this radius is comparable to that of the BH, and thus around one percent of the total mass of the cluster.

In case of $m_{BH} = 0.014M$, the core radius r_c is reduced in $\approx 4 t_{rh0}$ from the initial value of 0.4 to 0.3 (in NBODY units). This is to be compared with a value of ≈ 0.1 reached without the BH; when a BH (with the same mass) but no primordial binaries are present r_c goes down to ≈ 0.28 .

After the first mild contraction all Lagrangian radii start to expand steadily and a self-similar regime sets in, with the half-mass radius growing in proportion to $\approx t^{2/3}$, in agreement with the theoretical argument given by Hénon (1965). The half-mass radius is thus marginally bigger (by ≈ 10 % at $24 t_{rh0}$) due to the presence of the BH; without a BH the half-mass expansion starts only after core collapse, which takes $\approx 10 t_{rh0}$ in that case. Conversely, if a BH but no binaries are present, the expansion rate of r_h is reduced by ≈ 20 %. A summary of the properties of our simulations is reported in Table 1.

4. PROPERTIES OF THE BINARY POPULATION

As the presence of the BH dominates the global dynamics of the cluster, the evolution of the binaries presents some remarkable differences from the scenario where no central BH is present. We can distinguish two phases.

The presence of a BH significantly accelerates the rate at which binaries are disrupted in the first few half-mass relaxation times (see Fig. 1). The reason is that binaries that pass near the BH can be quickly destroyed. The disruption rate is approximately constant during the first 5 t_{rh0} , while without a BH disruption takes a while to get underway. The initial disruption rate depends on the mass of the BH: a more massive BH starts burning binaries at a higher rate, as can be seen from Fig. 1.

For our simulation with $m_{BH} = 0.014M$ we observe a binary depletion rate of ≈ 0.15 binaries per initial half-mass crossing time, during the first 5 t_{rh0} (80 binaries in total). Around half of the binaries are disrupted within r_i . Interestingly only two of them happen to be so close to the BH tidal radius r_t that the disruption may be considered a direct consequence of the tidal stripping force exerted by the BH. Here $r_t = (m_{BH}/m)^{1/3}a \approx 5a$, where a is the semi-major axis of the binary. With this respect, the theoretical model recently proposed by Pfahl (2005) applied to our simulation would give (from his Eqs. 11-12) a tidal disruption rate of $\approx 2 \cdot 10^{-2}$ binaries per initial half-mass crossing time, so that we observe

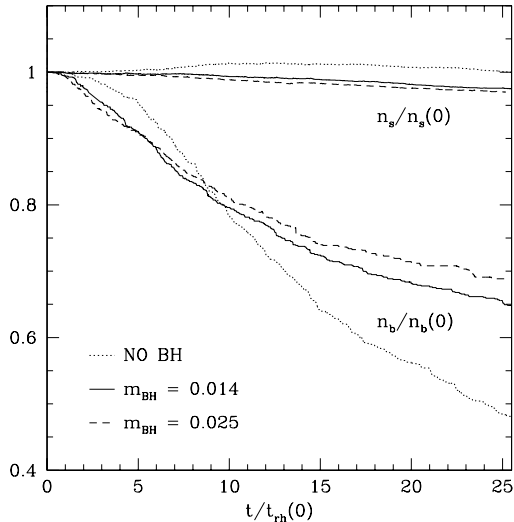


FIG. 1.— Time-dependence of the number of single (upper set of lines) and binary stars (lower set of lines) expressed as a fraction of the initial values. The data refer to simulations with $N = 8192$ and 10% primordial binaries. There are three choices for BH mass: no BH (dotted line), a central BH with $m_{BH} = 0.014M$ (solid line), and $m_{BH} = 0.025M$ (dashed line). The unit of time is the initial half-mass relaxation time.

less tidally stripped binaries than expected (≈ 10). The disruption of binaries by the BH is thus mainly due to an indirect effect: binaries venturing close to the BH, where the density is higher, are more likely to interact with a single star or with another binary. In fact in our simulations we often observe the presence of hierarchical systems within r_i , with the BH playing the role of a perturber.

After the initial transient phase a self-similar expansion sets in, where the average core density is much less (approximately by a factor 10) than it would be without the presence of a central compact object. In this second phase we observe (see Fig. 1) a reduced rate of binary disruption (as this rate is proportional to the square of the density, e.g. see Vesperini & Chernoff 1994), so that the difference between a simulation with and without a BH becomes remarkable. The turning point is around $10 t_{rh0}$, when the number of surviving binaries for a simulation with a central object becomes greater than in the absence of a BH. Our Fig. 1 has been given in units of the initial half-mass relaxation time, but the picture remains qualitatively the same even if we consider a co-moving time coordinate to take into account the differences between the half-mass radii of a simulation with and without a BH.

Interestingly the spatial distribution of binaries is also different from the case without a BH: as can be seen from Fig 2, the number of binaries within the 0.05 Lagrangian radius is much less for the simulation with a BH. This is probably due to the disruption of binaries that approach close to the BH. In the presence of a BH, binaries tend to be more concentrated between the 0.05 Lagrangian radius and the half-mass radius, while in the absence of a BH, binaries can sink deeper into the central region of the cluster. As a result, the ratio of binaries to singles in the core of the system is between two and three times

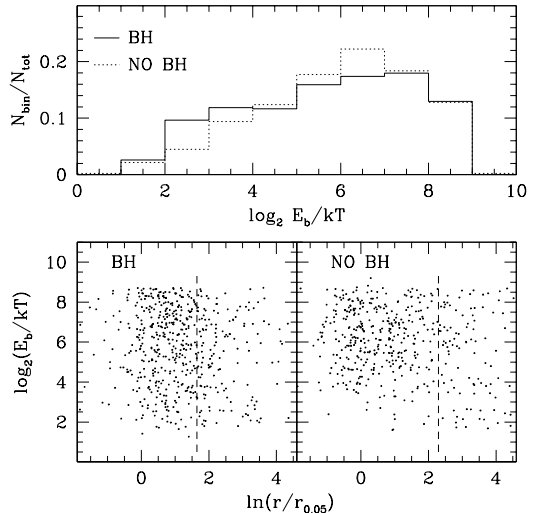


FIG. 2.— Distribution of binding energies for binaries (upper panel) at time $t = 24 t_{rh}(0)$ for a simulation with $N = 8192$, 10 % primordial binaries and $m_{BH} = 0.014M$ (solid line), compared to a similar simulation without the BH (dotted line). In the lower two panels we report the energy-radius distribution of binaries for the same simulations. The radii have been normalized to the Lagrangian radius containing 5 % of the mass in the simulation. The dashed line gives the position of the half-mass radius, at $t = 24 t_{rh0}$. The relatively large survival at $t = 24 t_{rh0}$ of binaries within the half-mass radius with binding energy $E_b < 20kT$ is clearly visible in the bottom panel, and is also reflected in the higher values for the solid line at the left-hand side of the upper panel.

less than in absence of the BH.

If we compare the evolution of the binding energy distribution of the binaries in a run with and without a central BH, we can see that the net effect of the BH at later times is to somewhat enhance the survival probability of binaries with binding energies of a few kTs ($E_b \lesssim 16 kT$), especially for binaries within the half-mass radius (see Fig. 2). This feature is especially apparent in a two-dimensional plot of the distribution of binaries as a function of binding energy and radial distance from the cluster center, depicted in the bottom panels of Fig. 2. The rather strong correlation between radius and binding energy that is observed (e.g., see Giersz & Spurzem 2000; Heggie et al. 2005) in systems without a central compact object is thus almost absent.

5. DISCUSSION AND CONCLUSIONS

In this paper we have presented for the first time the results of direct N-body simulations of the evolution of a globular cluster with a population of primordial binaries that harbors a central IMBH, with a mass of the order of 1 % of the total mass of the system. In order to begin to analyze the basic evolutionary processes we have restricted our simulations to isolated systems of stars of equal mass, while for the time being neglecting stellar evolution and physical collisions.

The environment around the BH turns out to be of great interest from a dynamical point of view. It represents a laboratory where complex interactions between hierarchical systems take place. Around the BH we observe usually one or more stars tightly bound to it. With a significant population of primordial binaries, it fre-

quently happens that a binary approaches the center of the system. Interactions between these subsystems are important not only from a dynamical point of view, but also because they form a factory to produce exotic objects, such as tight (X-ray emitting) binaries and high velocities escapers, which we observe in high numbers in our simulations. In our run with $m_{BH} = 0.014M$ we find that a fraction of $3 \cdot 10^{-3}$ of the stars of the cluster leave the system in a relaxation time and that $\approx 1/3$ of them have escape velocities that exceed by at least five times the core velocity dispersion. Of these 54 were binaries; in addition one triple was ejected from the system.

From a computational point of view the complex interactions between binaries and the BH have proved to be very challenging for current state of the art N-body algorithms. Clearly, new methods have to be developed to provide both more accuracy and higher efficiency.

We have shown that a BH with a mass of around 1 % of the cluster mass can produce most of the energy required to fuel the expansion of the globular cluster, so that the evolution of the large scale structure of a globular cluster with primordial binaries and a central BH is remarkably similar to that attained in the absence of binaries (see Baumgardt et al. 2004a). Even so, the evolution of the population of primordial binaries is strongly influenced by the BH, so that in principle indirect evidence for the presence of the BH can be obtained by observing the distribution of binaries.

Observational detection of an unexpectedly large number of only moderately hard binaries in the core could be used as arguments for the presence of a IMBH in old star clusters, i.e. in those systems whose age would imply a depletion in the central region of binaries with binding

energy below $\approx 15 kT$. These binaries are able to survive in significant numbers when an IMBH is present.

Clearly, a quantitative comparison with observations would require us to proceed beyond the simple models presented here. To start with, we would need to include a realistic number of stars to avoid possible biases introduced by the scaling of the ratio of the BH mass to that of single stars. In addition, the introduction of a realistic initial mass function is likely to modify the concentration of binaries in the center of the system due to mass segregation, and stellar evolution will also influence the distribution of binary binding energy. However, the main effects presented in this letter are likely to be present, at least in qualitative ways, in more detailed realistic simulations.

We are indebted to Sverre Aarseth for providing his code NBODY-6 with ad-hoc modifications in order to make possible running the simulations presented in this work. We thank Holger Baumgardt for interesting discussions. This work is supported in part by the Grants-in-Aid of the Ministry of Education, Science, Culture, and Sport, (14079205; MT, EA, SM) and by a Grant-in-Aid for the 21st Century COE “Center for Diversity and Universality in Physics” (SM). P.H. thanks Prof. Ni-nomiya for his kind hospitality at the Yukawa Institute at Kyoto University, through the Grants-in-Aid for Scientific Research on Priority Areas, number 763, “Dynamics of Strings and Fields”, from the Ministry of Education, Culture, Sports, Science and Technology, Japan. The numerical simulations have been performed on the Condor cluster at the Institute for Advanced Study.

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